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Development and Testing of Physically-Based Methods for Filling Gaps in Remotely Sensed River Data: Annual Report Year 2

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LONG-TERM GOALS

The long-term goal of the work described here is to develop and test a general methodology for predicting unmeasured river characteristics using a variety of potentially incomplete remotely sensed data sets. Rather than addressing the problem using various geostatistical techniques to interpolate and extrapolate the remotely sensed data, we are developing two physically based techniques, each of which can be used to fill in missing or incorrect segments of remotely sensed data sets. The first method is based on using the conservation equations for mass and momentum to fill in various kinds of missing information and the second is based on using computational morphodynamics (coupled flow and bed evolution predictions) to identify and fix errors in remotely sensed bathymetry. Both methods develop estimates of hydraulic and morphologic variables that satisfy conservation of mass and momentum. Importantly, we believe these methods can integrate a variety of different kinds of information, rather than concentrating on a single input data set or a desired output variable. Thus, although most of our initial work is aimed at resolving bathymetry, our goals are more general.

Our work in this area has been motivated by our earlier efforts in characterizing errors in bathymetric data in rivers collected using remote sensing (i.e., bathymetric LiDAR and various optical correlation techniques using multi- and hyperspectral scanning, as reported in Wright and Brock (2002), Kinzel et al., (2007), Legleiter and Roberts (2005), and Legleiter et al., 2004)). Comparison of the remotely sensed techniques with ground truth data obtained using conventional surveying techniques showed systematic errors that are associated with missing and/or incomplete information, especially in deeper areas where our remote sensing techniques fail due to attenuation in the case of LiDAR and due to a simple lack of resolution for the optical scanning techniques. In both cases, we could see that the bathymetric errors could probably be detected and potentially fixed using some simple post processing techniques involving conservation of flow momentum and morphodynamics modeling of the river bed. Thus, our initial efforts in this area have been directed at correcting bathymetry, but as we explored those possibilities and were also exposed to other types of remotely sensed data, we realized that the methods could potentially be generalized to include other kinds of remotely sensed data, including surface velocity, water-surface elevations, water's edge locations, or Lagrangian drifter tracks.
With these ideas in mind, our goals for this two-year effort are to develop the two approaches and to test them with appropriate field and laboratory data.

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OBJECTIVES

The specific objectives of the research work carried out under this grant are to develop and test two methods for filling in gaps in remotely sensed river data. The first method is based on developing a new numerical method to fill in missing information in remotely sensed data sets using the equations expressing conservation of mass and momentum. The second method is based on using existing models for coupled computations of flow, sediment transport, and bed evolution to predict where remotely sensed data is likely to be incorrect and to repair errors using predictions of morphologic evolution of the bed. This second method is directed primarily at errors in bathymetry, although we believe it could potentially be used in conjunction with the first method to repair other kinds of remotely sensed information. During the first year of this grant, we developed and tested the second method by using existing river bathymetry data sets to evaluate the capability of morphodynamics models for finding and correcting errors. In addition, we collected data sets in the laboratory and in the field suitable for testing both methods. During the second year of the grant covered in this annual report, our primary objective was to develop and test the first method following the procedure discussed in our original proposal. As we were working through that process and understanding the sensitivities of the inversion technique to the data, we developed the secondary objective of measuring water-surface velocities with greater resolution and directed some of our efforts on new methods to collect the data needed for the inversion technique.

APPROACH

Our objective for year 1 of this grant was to test the idea of using morphodynamics to find and correct errors in remotely sensed data, as reported by Nelson et al. (2011). Achieving this goal was relatively straightforward, as we had pre-existing river surveys including both remotely sensed and conventionally surveyed data, as well as a suite of well-tested morphodynamics models to apply. For year two, we wanted to develop and test a method that only used conservation of momentum for the flow, which required developing a new inverse model for predicting bathymetry from quantities that can be measure remotely. This technique does not depend on using morphodynamics, but it does require some additional information about the flow in terms of water-surface elevation and velocities. The general idea is that depths can be determined or corrected based on other information about the flow and simple conservation laws. The other information required may be in the form of water-surface elevation, flow velocities, or a combination of the two along with some depth information. For this case, the equations expressing conservation of mass and momentum for the flow can be solved (typically numerically) with available information to place constraints on local depth or identify and fix errors in depth estimates.

After investigating a few different techniques for performing this sort of inversion, we concluded that the simplest method was a good place to start. Instead of using a computational inversion that solves for depth based on a full partial differential equation, the equations expressing conservation of mass and momentum were simplified based on a few reasonable assumptions to give expressions that directly predict local flow depth as a function of water-surface elevation and vertically averaged velocity. For example, from the streamwise component of the equation expressing conservation of momentum for river flow, if we assume the flow is incompressible and quasi-steady, has no lateral stresses, and that a simple drag coefficient closure is suitable, we can directly obtain an equation relating local depths to local hydraulic variables, as follows:

$$h = \frac{-C_d\sqrt{<u>^2 + <v>^2}\,<u>}{\left[\frac{g}{1-N}\frac{\partial E}{\partial s} + \frac{<u>}{1-N}\frac{\partial <u>}{\partial s} + <v>\frac{\partial <u>}{\partial n} - \frac{<u><v>}{(1-N)R}\right]}$$

where N is a simple metric coefficient, R is the centerline radius of curvature of a channel-fitted centerline, g is gravity, C_d is a drag coefficient, <u> and <v> are vertically averaged velocity components in the streamwise and cross-stream directions, and s and n are coordinates locally oriented in the streamwise and cross-stream directions, respectively.

To test the expressions and investigate potential errors, we initially applied them to data sets developed from existing river models. Measured bathymetry was used to compute flows of a certain discharge in river channels using open-source, public domain model FaSTMECH (Nelson and McDonald, 1996; Nelson, Bennett and Wiele, 2003; McDonald, 2006) available in the International River Interface Cooperative (iRIC; www.i-ric.org) river modeling package developed by our group and others. The predicted water-surface elevations and vertically averaged velocities were extracted from the model results and the depth was predicted from that information using the formulation above. While this is clearly circular, it allows us to start with data sets that are constrained to satisfy conservation of mass and momentum and, as discussed in one of our publications (Nelson et al, 2012), it provides some good physical guidance on issues with the approach and the effect of noise in the driving data.

We developed results of this process for two very different river reaches: the Trinity River in California, which is a relatively steep, shallow, coarse-bedded channel, and the Kootenai River in Idaho, which is a relatively flat, deep, sand-bedded reach. For each river, the inversion technique was applied directly to compare the computed and measured depths. The impacts of normally distributed noise in the input data sets (water-surface elevation and velocity) was also explored. Finally, the impact of using surface velocity instead of vertically averaged velocity in the inversion method was investigated. Some of these results are summarized briefly below and the rest are presented in Nelson et al. (2012).

As might be expected, our results show that this simple inversion technique requires very accurate input data on water-surface elevation and velocity. With this in mind, a parallel effort on lab and field measurement of the required input data was initiated. In previous work, we have used videographic and acoustic methods for determining water-surface elevations, and mechanical current meters, acoustic current meters, LDV and PIV methods for measuring flow velocities. However, because this method is ultimately intended to use remotely sensed data and because it requires spatially dense information for application, we recognized the need for other techniques for collecting input data. We investigated a few possibilities and decided that surface velocity measured using infrared videography (Dugan and Piotrowski, 2003) looked promising for remote collection of the velocity field. For water-surface elevation, current lab techniques were sufficient, but we started to investigate and learn about interferometric radar techniques for collecting accurate field data, with particular emphasis on the SWOT technology being developed by NASA.

WORK COMPLETED

Based on research efforts over the first 9 months of the second year of our ONR grant, the following tasks are complete:

(1) We developed a numerical evaluation method for the solution of the simple inversion approach described above.

(2) We applied the simple inversion technique for depth for the Trinity River, a relatively steep, coarse-bedded river in northern California.

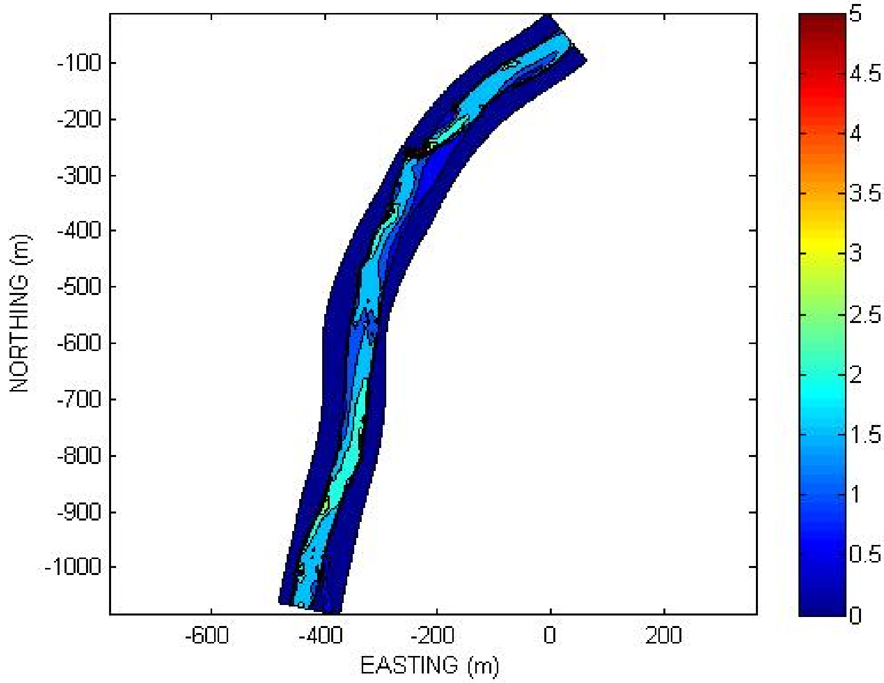
(3) We applied the simple inversion technique for depth on the Kootenai River, a relatively flat, san-bedded channel in northern Idaho.

(4) We tested infrared videography combined with PIV methods to measure detailed water-surface elevations in a laboratory setting.

(5) We collaborated with Arete to measure field water-surface velocities using infrared videography on the confluence of the Colorado and Blue Rivers in Colorado.

RESULTS

Figure 3 shows measured contours of depth from the field survey of the Trinity along with the prediction of depth from the equation above. This expression was evaluated using simple backward differences for the derivatives of elevation and vertically averaged velocity components. As one might expect, the predictions of depth are very good in the central parts of the channel (where the assumptions leading to the simple inversion equation are most likely to be correct), but relatively poor near the banks. This is primarily due to neglecting lateral stresses, but may also be due to the poor discretization and relatively imprecise conservation of mass and momentum near the boundary cells of the FaSTMECH model, which does not employ a cut cell or other sophisticated technique to deal with crude resolution of the bank by the finite-difference grid.



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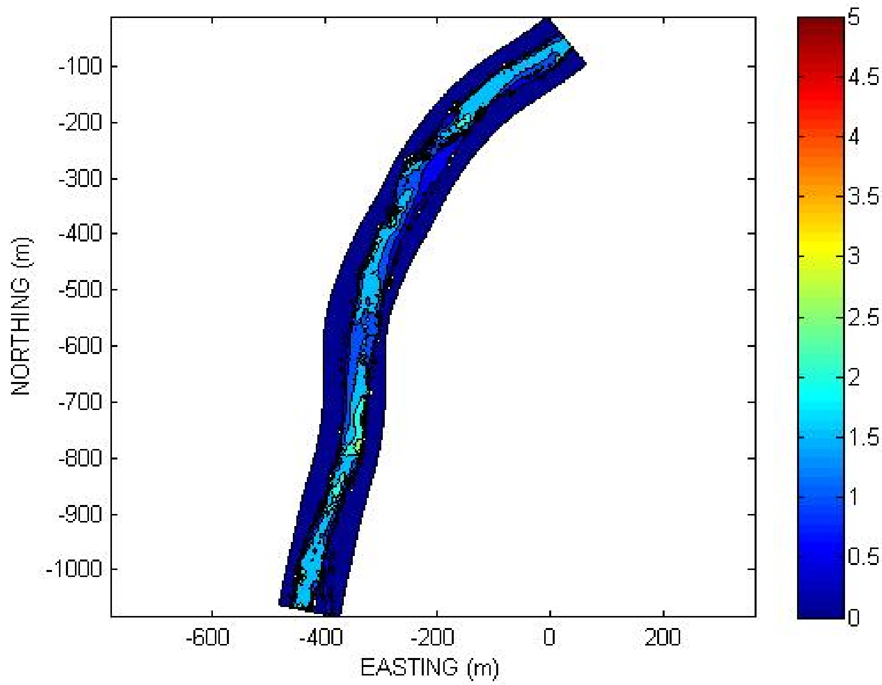

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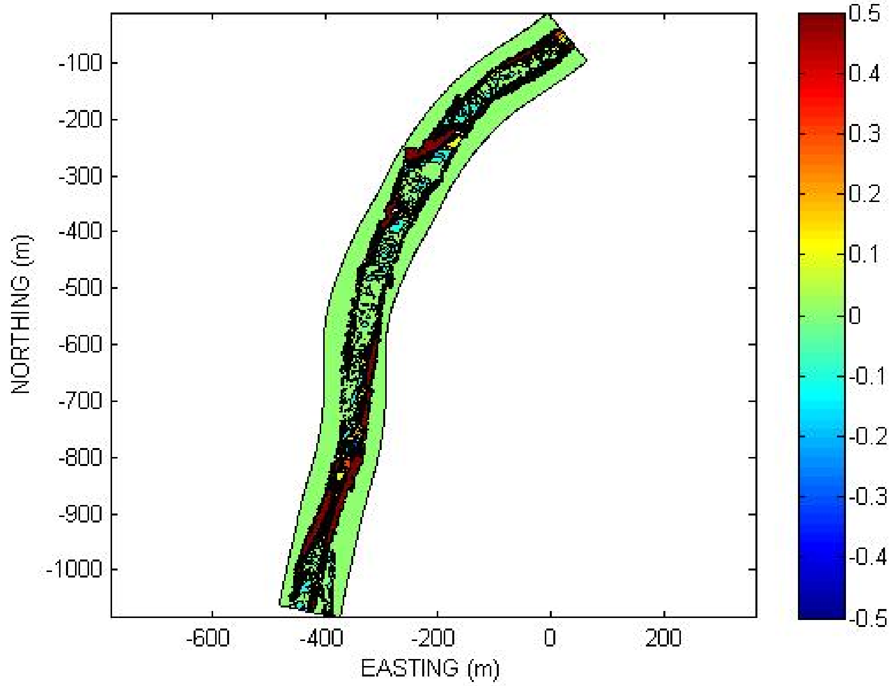

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Figure 1. Measured depth (A) and predicted depth (B) using Equation (15). Errors are shown in (C). Depths in meters.

The root-mean square (rms) error between the measured and predicted depth is 0.56m (computed only from wetted points in the model domain). The average depths in this reach of the Trinity are less than 2m, so this is a large error. However, the pattern of errors shown in Figure 1C shows that significant errors in the depth occur primarily near the banks and other regions of strong lateral shear. In these areas, the inversion tends to predict a lower depth than actually present due to the absence of lateral stress terms; velocities and stresses near the banks are low in the model predictions relative to the simple force balance represented in the simplified equation, so the depth is underpredicted. Other than this effect, the predictions are quite good, with errors of less than 0.1m of the average depth over most of the channel away from the banks, as shown in Figure 2. We are currently working on improving this approach by including the lateral stress terms iteratively.

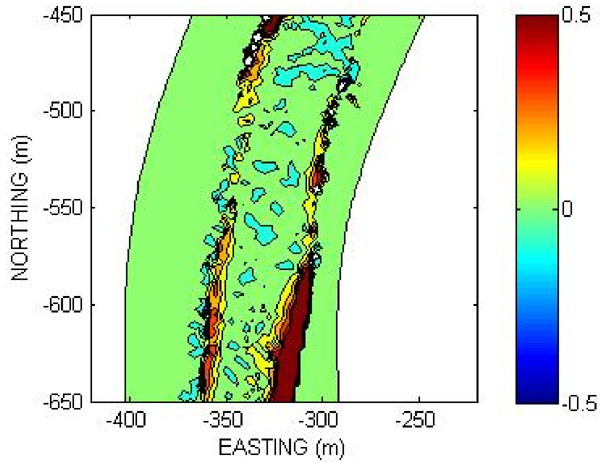

Figure 2. Detail of errors in depth prediction (meters).

A similar inversion was carried out using model results from the Kootenai, which is a much deeper (typically 10m) river with a lower slope and finer bed material. As with the Trinity River, depths were predicted using velocities and water-surface elevations from model runs. The root-mean square error in the depth prediction was 2.66m, which is greater than that found in the Trinity case, but a similar percentage of the mean depth. However, as shown in Figure 3, although the error associated with lateral stress effects is still important, there is another more spatially pervasive effect causing errors. This error is associated with the bedforms mantling the bottom of the Kootenai reach. Figure 4 shows the bed morphology in the region of Figure 3; bedforms of 1-2m in height are present in this reach. The hydrostatic flow model cannot capture the effects of these features, and the free surface response to them is small, typically only a few mm of water-surface elevation. Even small model errors (consistent with single precision values) are large enough to produce large errors in the depth prediction. Investigation of this effect requires application of a non hydrostatic model and using higher precision in the model results.

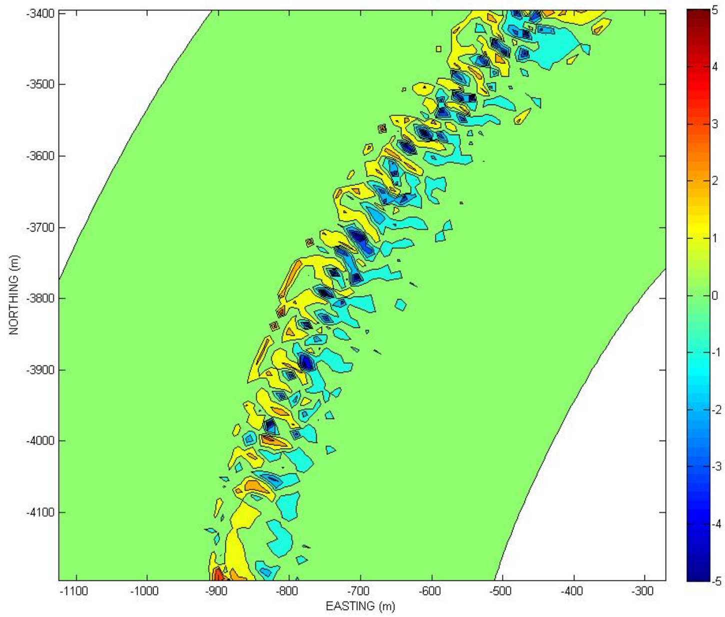

Figure 3. Detail of the error between predicted and measured depth (m) for a short section of the Kootenai reach.

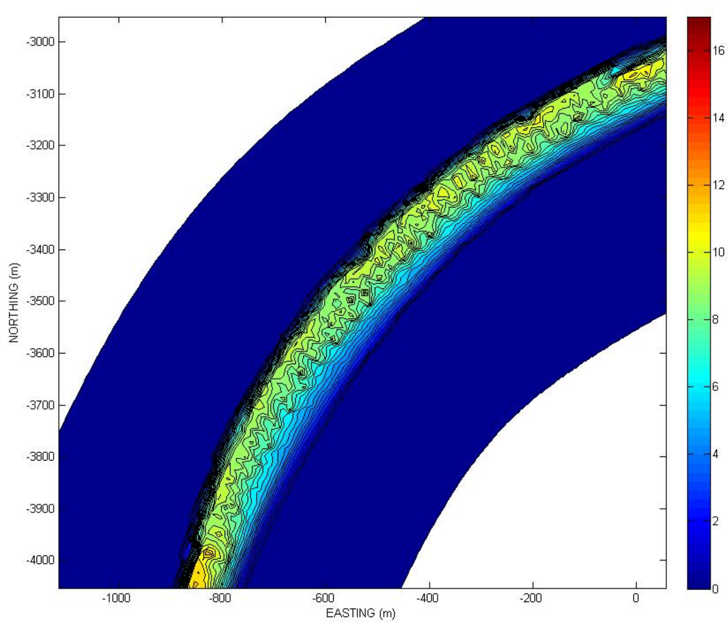

Figure 4. Bed elevation contours (m) for the section of the Kootenai shown in Figure 3.

After carrying out the inversion on the Trinity and Kootenai using synthesized data, the method seemed promising enough to warrant some more realistic testing using lab and field data. However, detailed data sets with sufficient accuracy were not available, so attention was focused on developing and applying methods to collect the required input data. In 2011, Areté Associates' Airborne Remote Optical Spotlight System-Fixed (AROSS-F) system was flown over a reach of the Blue and Colorado Rivers. AROSS-F used a combination of visible electro-optical (EO) and mid-wave infrared (MWIR) cameras to acquire imagery of the water surface (Figure X). Velocities from the high resolution MWIR cameras were computed using a maximum cross-correlation (MCC) algorithm. These AROSS velocities were compared to acoustic Doppler current profiler (ADCP) surface velocities along a reach of the Colorado River downstream of the Blue confluence. The velocity magnitudes calculated from the AROSS/ADCP comparison had a mean bias of -0.01 m/s and RMS difference of 0.06 m/s. The direction bias of velocity vectors was determined to be 8.4° and the RMS difference was 11.9° (Figure X). The discrepancy in current direction may be related to the compass calibrations, or the disparate methods used to sample the surface velocity. Further information on this work appears in Kinzel et al. (2012).

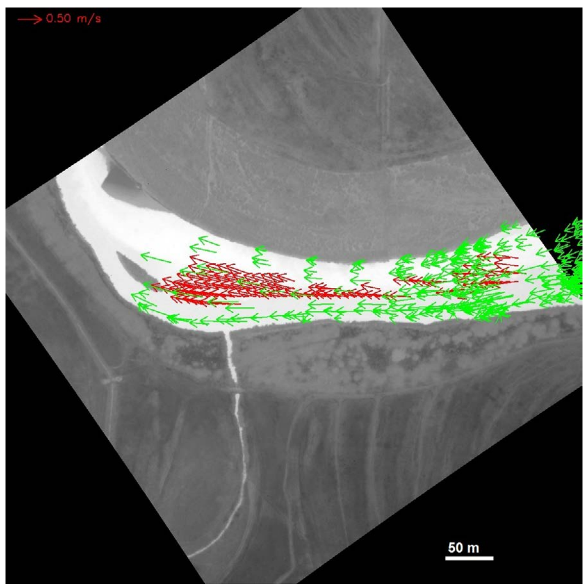

Figure 5: Mapped image showing surface velocity vectors measured with the ADCP (green) and those derived from AROSS image data (red).

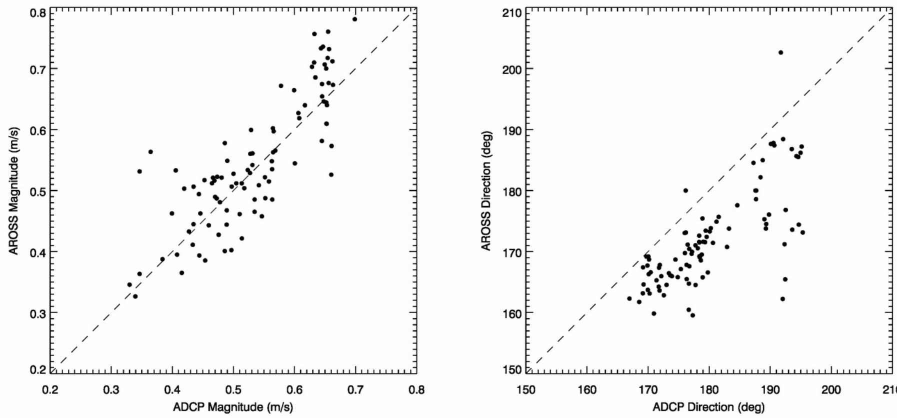

Figure 6: Comparison of surface velocity magnitude and direction measured with the AROSS and ADCP sensors.

To further our understanding of the use of thermal imaging technologies for the detection of surface currents, we conducted laboratory experiments using a FLIR SC8303 demonstration camera. This mid-wave infrared FLIR camera is similar to that used in the AROSS-F system. In these experiments, we pointed the camera obliquely at a short segment (0.4 by 0.5 m) of a 7-meter long flume at the Geomorphology and Sediment Transport Laboratory (GSTL) in Golden, Colorado. Figure X shows an image of the water surface temperature with flow over of sand bed at a rate of 1L/s. A variety of frame rates were collected and we experimented with multiple lenses to provide sample datasets for testing particle imaging velocity (PIV) software for computing surface velocity. Initial results using commercially available PIV software (PIVTEC's PIVview 2C) are encouraging. Our current focus is optimizing the settings available in the software to produce spatially explicit velocity maps for use in the depth inversion technique.

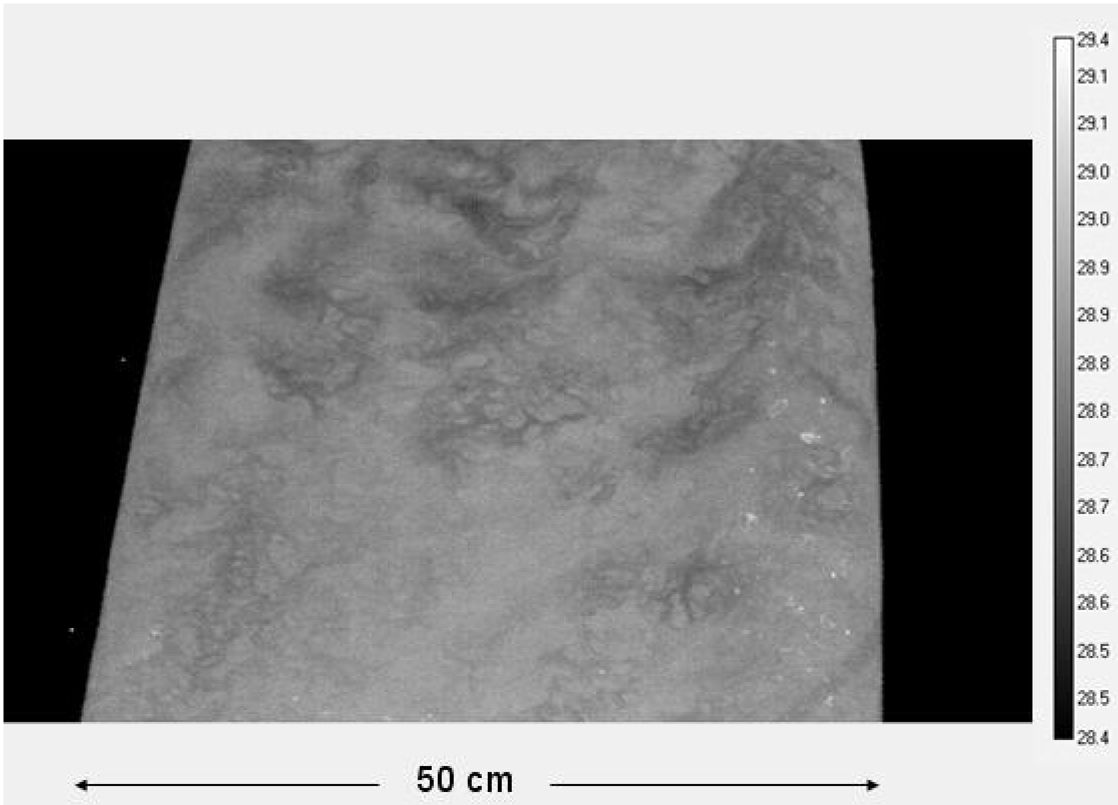

Figure 7. Image of surface temperature, in degrees Celsius, over a segment of the GSTL flume. Flow is from bottom of the image to the top.

In addition to exploring these techniques for measuring detailed surface velocities, some preliminary work on measuring field water-surface elevations with laser scanners was completed. This was done because, even though we had accurate methods for measuring detailed water-surface elevation in the lab, the techniques are not amenable to application over large field areas; using a laser scanner is potentially a good field method, although we were unable to find previous work where this method had been applied and tested with other measurements. We carried out one data collection effort on the Platte River in October, 2012 and were able to show that the scanner can measure surface elevations very quickly over an entire reach. We are currently working on averaging that data to compare it to ground measurements and model predictions.

Finally, as part of the same effort to develop field techniques for measuring water-surface elevation, we spoke with researchers on the NASA AirSwot program and were instrumental in planning a combined effort for data collection on the Sacramento River this coming April. AirSwot surface elevation data will be collected and USGS will work on collecting both truth data for comparison and bathymetry and velocity. We hope to include some component of infrared visdeography for water-surface velocities, but this is uncertain at this point.

IMPACT/APPLICATIONS

As the end of this grant period nears, the work performed has demonstrated (1) the feasibility of using morphodynamics models in conjunction with remotely sensed data for making estimates of bathymetry and other river characteristics and (2) the possibility of using inverse models to compute bathymetry in rivers from surface-based information on elevation and velocity. All the river modeling tools used in this project are available in the iRIC public-domain software package and programmers are currently working on adding the inversion technique to that same platform. The first step in testing the inversion method with data synthesized from model results has been completed, and current work is actively pursuing the development of both lab and field data sets for further applications and testing. Based on what has been learned, improvements to the method addressing the lateral stress terms are in development.

RELATED PROJECTS

Project personnel coordinated with Arete Associates prior to and during deployment of their RiverEye/AROSS system. Our project along with USGS personnel in Grand Junction provided field support for Arete's collections in Colorado. The field support included coincident in situ measurements of bathymetry and velocity in the Blue, Colorado, and Yampa Rivers with ADCP and ADV instrumentation. The acoustic measurements of velocity made at these sites have been compared to Arete's remotely sensed surface currents. Additional ancillary data including streamflow, river stage, gage datums, and bathymetry was provided to support Arete's collections on the Kootenai, Green, and Columbia Rivers.

A comprehensive multibeam bathymetric survey was acquired in June of 2011 on the Yampa River near Deerlodge Park to support a USGS surface-water modeling study. Similar modeling projects on the San Joaquin and Sheboygan River were aided over the course of this grant by multibeam bathymetric mapping expertise provided by project personnel. These new projects further expand the existing catalog of high resolution hydrographic surveys available for comparison to remotely sensed bathymetry. Our project continues to make our data holdings available to collaborators and students like Lt. Matthew Pawlenko at the Naval Postgraduate School, who made use of our Trinity River data for his thesis.

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